



US009190708B2

(12) **United States Patent**
Parmon

(10) **Patent No.:** **US 9,190,708 B2**
(45) **Date of Patent:** **Nov. 17, 2015**

(54) **SYSTEM FOR REDUCING
ELECTROMAGNETIC INDUCTION
INTERFERENCE**

6,933,812 B2 8/2005 Sarabandi et al.
7,215,007 B2 5/2007 McKinzie, III et al.
8,816,798 B2 * 8/2014 McKinzie, III 333/251
2004/0239451 A1 * 12/2004 Ramprasad et al. 333/202
2007/0215843 A1 9/2007 Soukoulis et al.

(71) Applicant: **Walter Parmon**, Chandler, AZ (US)

(72) Inventor: **Walter Parmon**, Chandler, AZ (US)

(73) Assignee: **Freescale Semiconductors, Inc.**, Austin,
TX (US)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 261 days.

(21) Appl. No.: **13/785,482**

(22) Filed: **Mar. 5, 2013**

(65) **Prior Publication Data**

US 2014/0253258 A1 Sep. 11, 2014

(51) **Int. Cl.**

H04B 3/28 (2006.01)

H01P 11/00 (2006.01)

H01P 1/20 (2006.01)

H05K 1/02 (2006.01)

(52) **U.S. Cl.**

CPC **H01P 11/007** (2013.01); **H01P 1/20**
(2013.01); **H01P 1/2005** (2013.01); **H05K**
1/0236 (2013.01)

(58) **Field of Classification Search**

CPC H01Q 13/10; H01P 11/007; H01P 1/20

USPC 333/12, 202

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,262,495 B1 7/2001 Yablonovitch et al.
6,906,674 B2 * 6/2005 McKinzie et al. 343/767

FOREIGN PATENT DOCUMENTS

KR 1020100034236 * 4/2010 H05K 1/02
KR 100965264 B1 * 6/2010 H05K 1/02

OTHER PUBLICATIONS

Jinwoo Choi; Vinu Govind; and Madhavan Swaminathan. "A Novel
Electromagnetic Bandgap (EBG) Structure for Mixed-Signal System
Applications." School of Electrical and Computer Engineering,
Georgia Institute of Technology, pp. 243-246, Atlanta, Georgia.

(Continued)

Primary Examiner — Sibin Chen

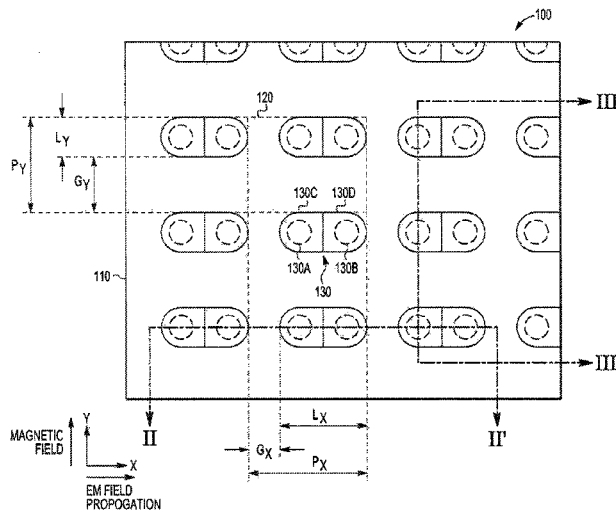
Assistant Examiner — Metasebia Retebo

(57)

ABSTRACT

An electromagnetic band gap device is provided, comprising:
a conductive plane; a non-conductive substrate located over
the conductive plane; and an electromagnetic band gap unit
cell that includes a first via located in the non-conductive
substrate and filled with a conductive material, a second via
located in the non-conductive substrate and filled with the
conductive material, a first conductive surface located on the
non-conductive substrate over the first via, and a second con-
ductive surface located on the non-conductive substrate over
the second via, wherein the electromagnetic band gap unit
cell is configured to operate as an LC resonant circuit in
conjunction with the conductive plane, at least one gap is
located in the electromagnetic band gap unit cell, the at least
one gap being located in the first via, in the first conductive
surface, in the second conductive surface, and in the second
via.

25 Claims, 7 Drawing Sheets



(56)

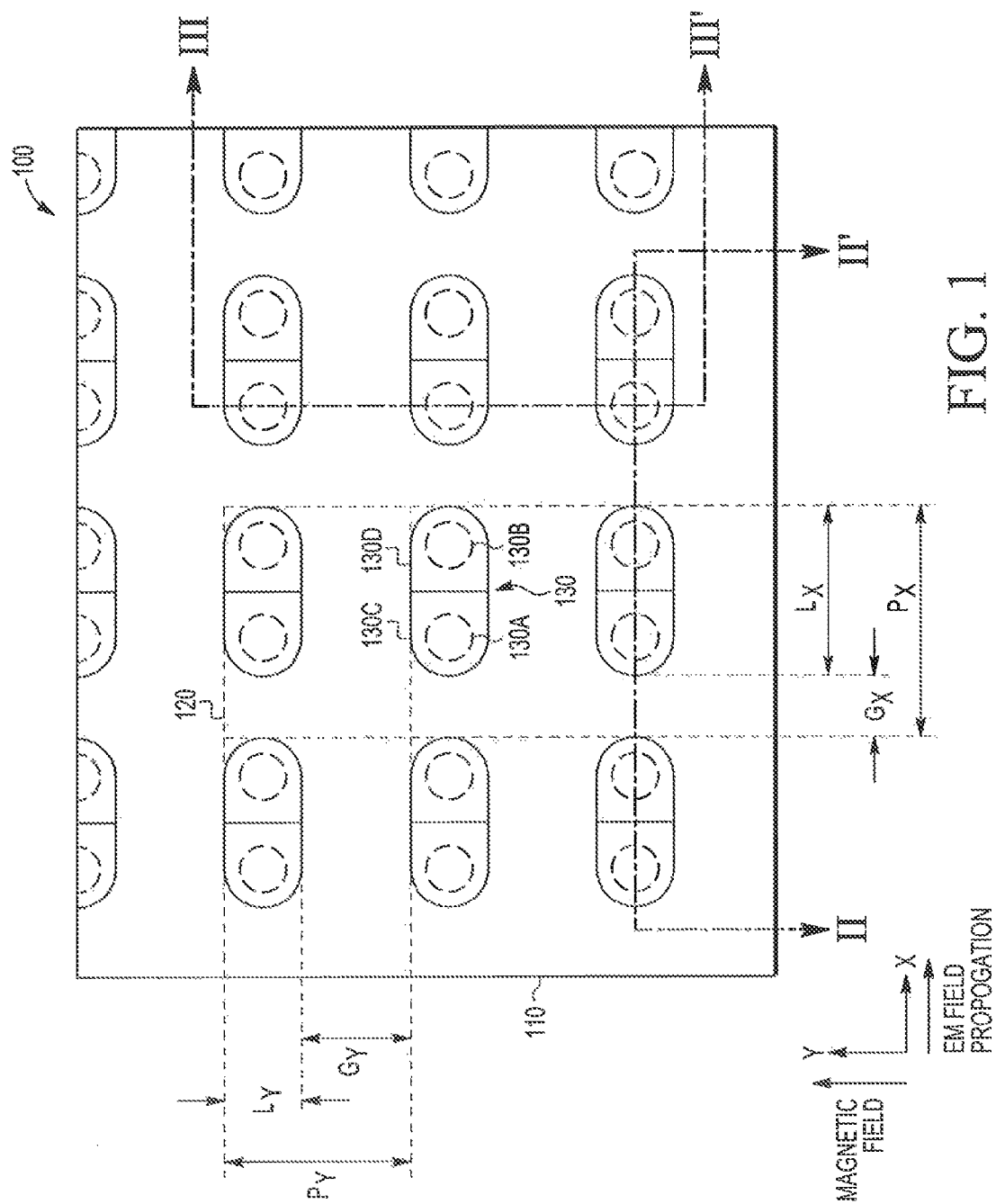
References Cited

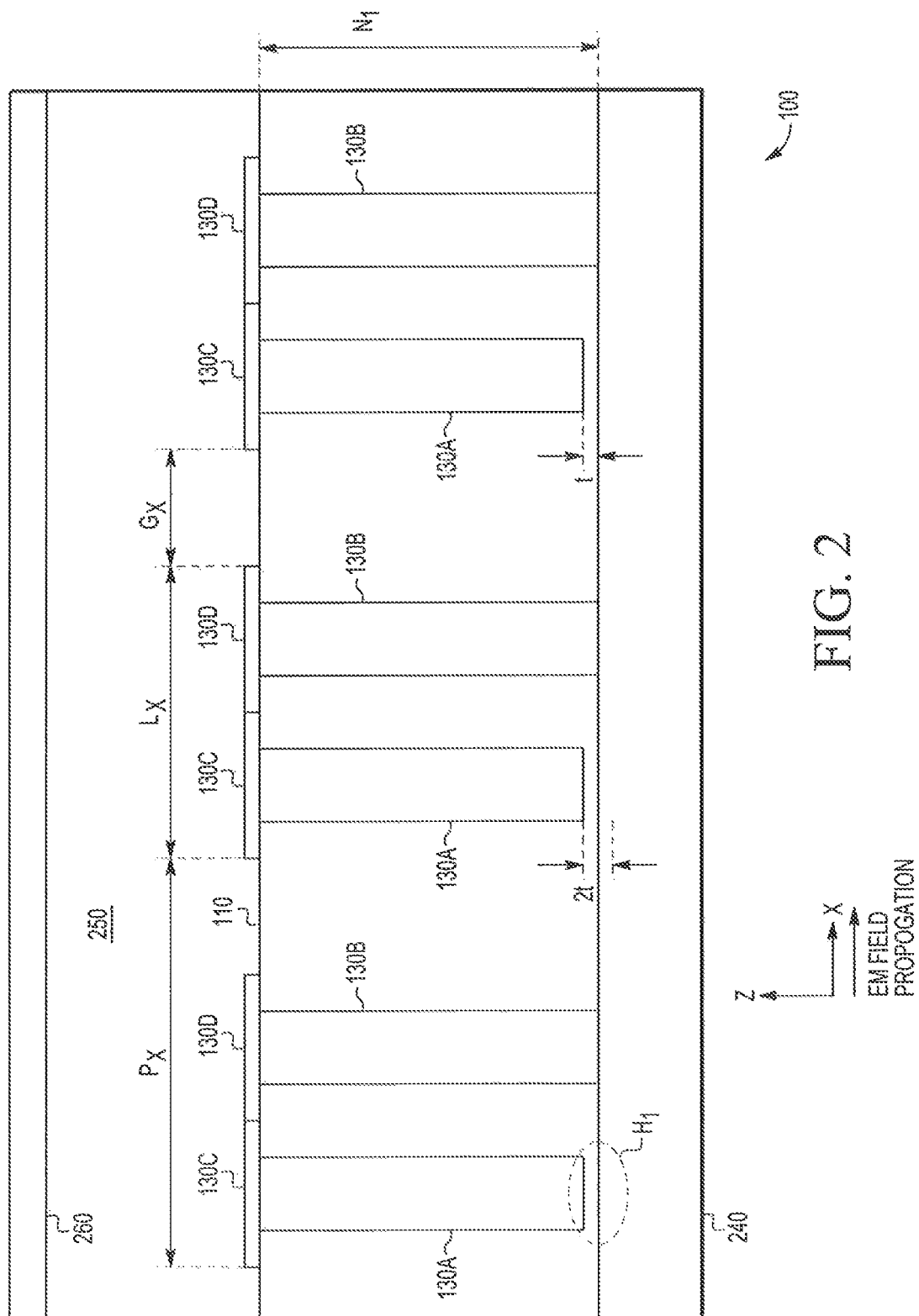
OTHER PUBLICATIONS

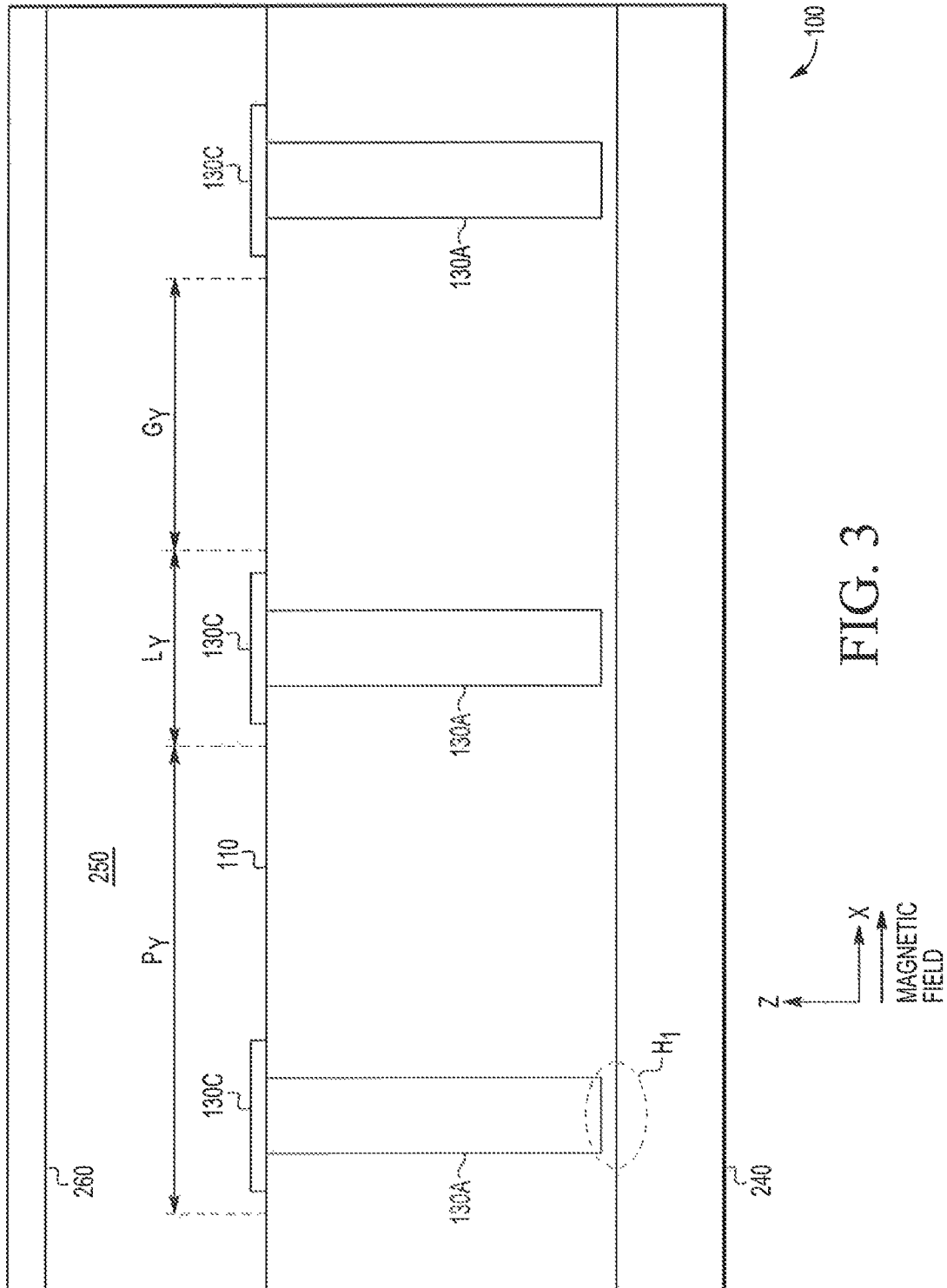
Hamada Elsaied and Maher M. Abd Elrazzak. "Novel Planar Microstrip Low Pass Filters Using Electromagnetic Band Gap (EBG) Structures." Middle East Conference on Antennas and Propagation (MECAP), Oct. 2010. Cairo, Egypt.

Mingchun Tang; Shaoqiu Xiao; Tianwei Deng; and Bingzhong Wang. "Novel folded single split ring resonator and its application to eliminate scan blindness in infinite phased array," Signals Systems and Electronics (ISSSE), 2010 International Symposium on Signals, Systems and Electronics, vol. 1, pp. 1-4, Sep. 2010.

* cited by examiner







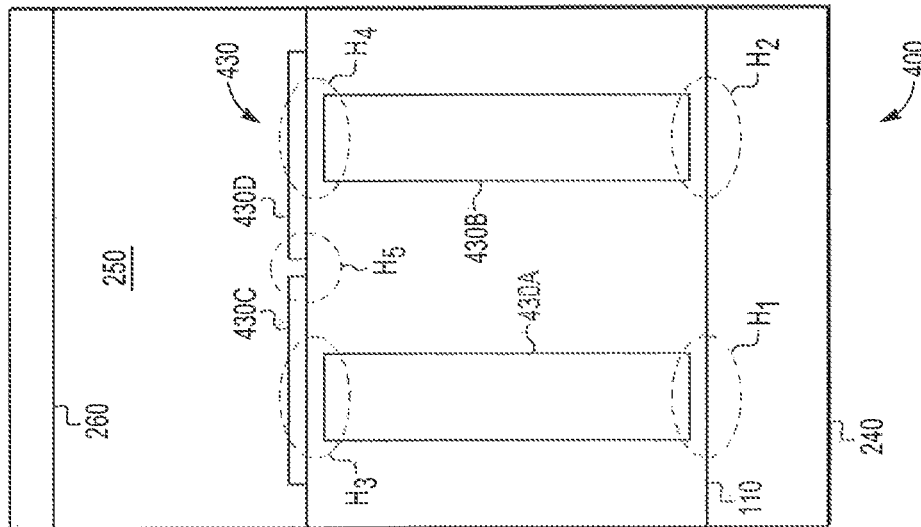


FIG. 4

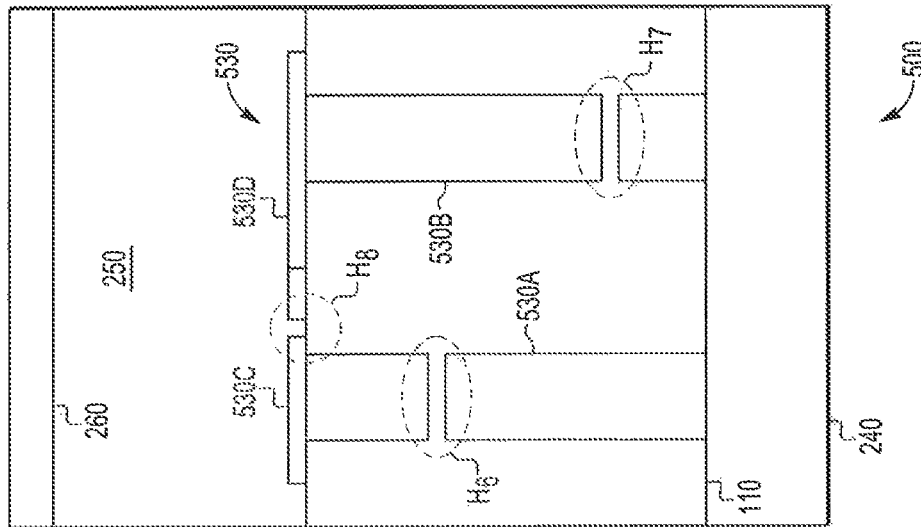


FIG. 5

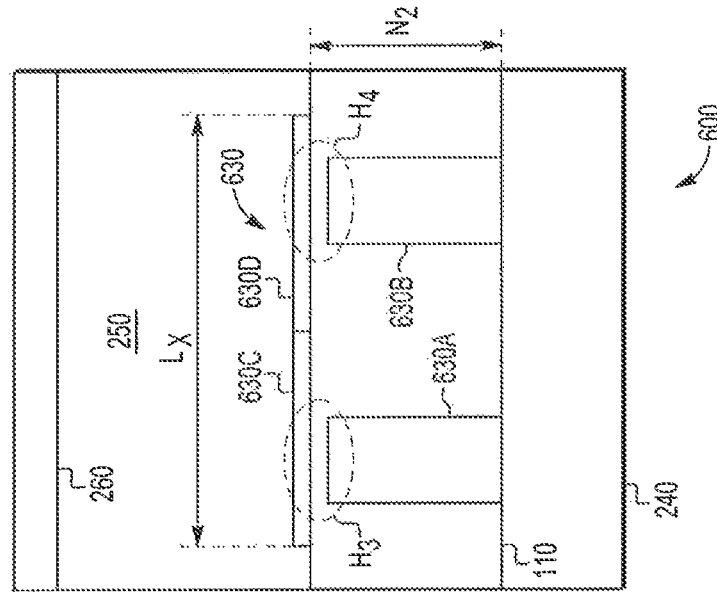


FIG. 6

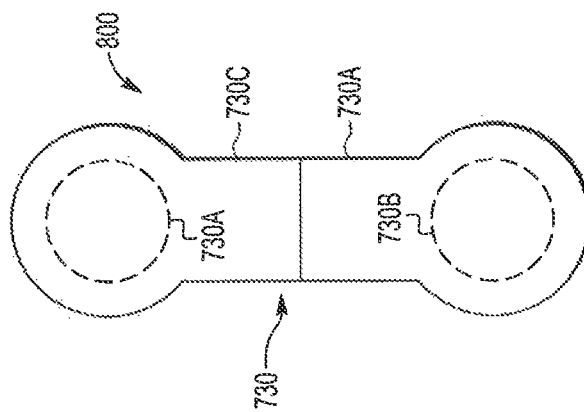


FIG. 7

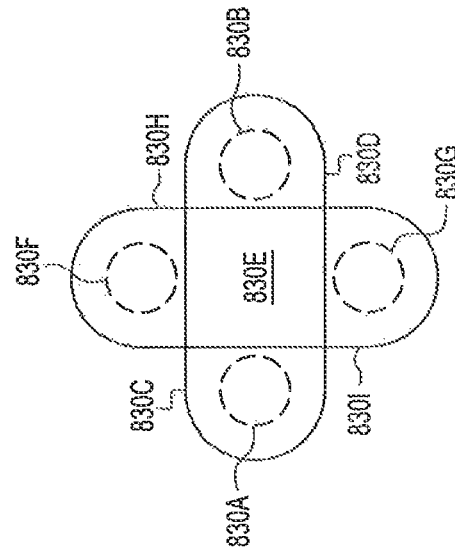


FIG. 8

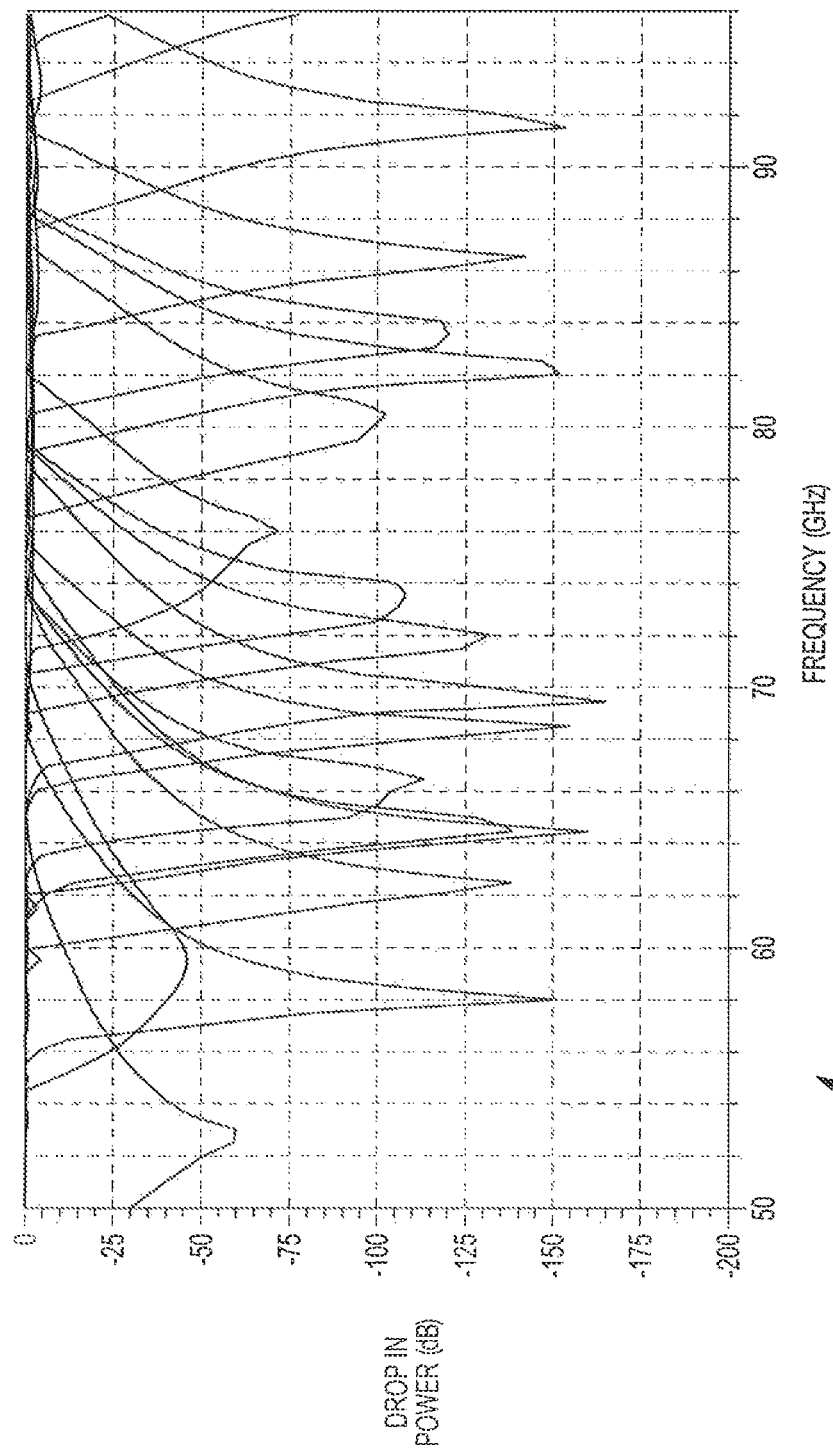


FIG. 9

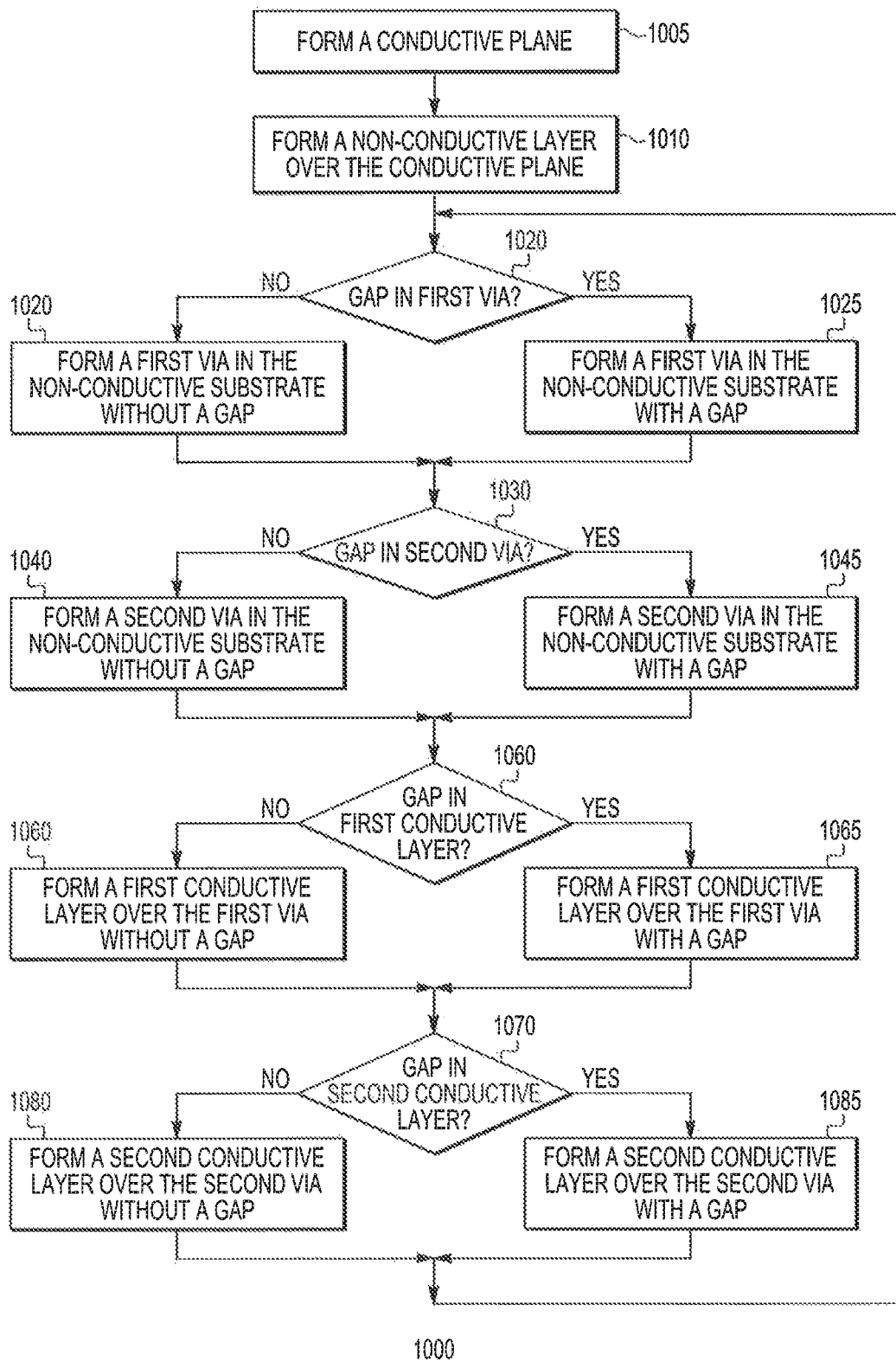


FIG. 10

1

SYSTEM FOR REDUCING ELECTROMAGNETIC INDUCTION INTERFERENCE

FIELD OF THE INVENTION

The present invention relates in general to a system for reducing electromagnetic induction (EMI) interference. In particular it relates to an electromagnetic band gap device located over a ground plane that suppresses EMI interference.

BACKGROUND OF THE INVENTION

When an integrated circuit (IC) is formed over a ground plane, there will be portions of the ground plane where electromagnetic (EM) energy scatters from the transitions caused by geometrical discontinuities and impedance mismatches on the IC. This can cause propagation of EM waves between the IC and the ground plane at certain interfering frequencies. If a radio frequency (RF) device is attached to the IC or operating near the IC, the EM waves caused by this EM energy can interfere with the of that RF device, particularly when the interfering frequencies are near the operating frequencies of the RF device.

For this reason, electromagnetic band gap devices have been designed to suppress and control the EM energy that causes the propagation of EM waves between the IC and the ground plane. An electromagnetic band gap device serves to create a band gap in the frequency spectrum of the propagating electromagnetic waves. This frequency band gap is designed to effectively eliminate interference in a desired frequency range by attenuating the potentially interfering signals to such a degree that they are below a threshold of interference. For example, when a radio or a radar device will be operating near the ground plane, the frequency band gap is provided in the operational frequency range of the radio or radar device.

One way of creating such a frequency band gap is through Sievenpiper electromagnetic band gap devices. Such devices resemble an array of tables formed over a ground plane, each of the tables having a single support rod holding it up.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying figures where like reference numerals refer to identical or functionally similar elements and which together with the detailed description below are incorporated in and form part of the specification, serve to further illustrate an exemplary embodiment and to explain various principles and advantages in accordance with the present invention. These figures are not necessarily drawn to scale.

FIG. 1 is an overhead view of an electromagnetic band gap device for reducing EMI interference according to a disclosed embodiment;

FIG. 2 is a cut-away view of the electromagnetic band gap device of FIG. 1 along the line II-II';

FIG. 3 is a cut-away view of the electromagnetic band gap device of FIG. 1 along the line III-III';

FIG. 4 is a side view of a unit cell in an electromagnetic band gap device according to disclosed embodiments;

FIG. 5 is a side view of a unit cell in an electromagnetic band gap device according to other disclosed embodiments;

FIG. 6 is a side view of a unit cell in an electromagnetic band gap device according to still other disclosed embodiments;

2

FIG. 7 is an overhead view of a loop element in an electromagnetic band gap device according to yet other disclosed embodiments;

FIG. 8 is an overhead view of a loop element in an electromagnetic band gap device according to still other disclosed embodiments;

FIG. 9 is a graph of electromagnetic band gap (EBG) suppression where the electromagnetic band gap frequency range is controlled by gap number, gap location, and unit cell parameters in an electromagnetic band gap device according to various embodiments; and

FIG. 10 is a flowchart of a method of manufacturing an electromagnetic band gap device according to disclosed embodiments.

DETAILED DESCRIPTION

The instant disclosure is provided to further explain in an enabling fashion the best modes of performing one or more embodiments of the present invention. The disclosure is further offered to enhance an understanding and appreciation for the inventive principles and advantages thereof, rather than to limit in any manner the invention. The invention is defined solely by the appended claims including any amendments made during the pendency of this application and an equivalents of those claims as issued.

It is further understood that the use of relational terms such as first and second, and the like, if any, are used solely to distinguish one from another entity, item, or action without necessarily requiring or implying any actual such relationship or order between such entities, items or actions. It is noted that some embodiments may include a plurality of processes or steps, which can be performed in any order, unless expressly and necessarily limited to a particular order; i.e., processes or steps that are not so limited may be performed in any order.

Electromagnetic Band Gap Device

As noted above, Sievenpiper electromagnetic band gap devices are conventionally used to suppress and control the EM energy that causes the propagation of EM waves between an IC and a ground plane. However, Sievenpiper electromagnetic band gap devices have the disadvantage in that they require a minimum height. This height is typically around 200 μm for a band gap near 80 GHz. This can be a significant problem when size of a device is an important design parameter, since the minimum height of a Sievenpiper electromagnetic band gap device serves as a limit as to how small the device can be.

It would therefore be desirable to provide an electromagnetic band gap device that could be manufactured to be thinner than a Sievenpiper structure. It would also be desirable for such an electromagnetic band gap device to be easily and cheaply manufactured, but to be capable of being implemented to locate the range of band gap suppression to a desired frequency range for interference suppression.

FIGS. 1 to 3 show an electromagnetic band gap device 100 for reducing electromagnetic induction (EMI) interference according to a disclosed embodiment. FIG. 1 is an overhead view of the electromagnetic band gap device according to the disclosed embodiment. As shown in FIG. 1, an array of unit cells 120 is provided in a non-conductive substrate 110 located above a conductive plane (240 in FIGS. 2 and 3). Each unit cell 120 includes a loop element 130 that is made up of a first via 130A, a second via 130B, a first conductive surface 130C, and a second conductive surface 130D.

The conductive plane 240 has an electromagnetic (EM) field propagating through it in a first direction (the X-direction in FIG. 1), and a magnetic field that is oriented in a second

3

direction (predominately the Y-direction in FIG. 1) perpendicular to the first direction. In the embodiment disclosed in FIG. 1, each of the loop elements **130** in each of the unit cells **120** is oriented such that a line made between the center of a circular cross-section of the first via **130A** and the center of a circular cross-section of the second via **130B** is in the X-direction (i.e., the direction of the propagation of the EM field). The conductive plane **240** is parallel to the X-Y plane.

The nonconductive layer **110** is an insulating material located over the conductive plane **240**, and is used, in part, to insulate the conductive plane **240** from the IC die **260**. The non-conductive layer **110** can be made of such materials as dielectrics (e.g., silicon dioxide, silicon nitride, polymers like polyimide, polymers loaded with ceramic, or combinations of layers of the forgoing list of materials or similar materials).

The unit cells **120** are arranged in a regular pattern in the nonconductive layer **110** to fill at least a portion of the non-conductive layer **110**. Each unit cell **120** has a loop portion that includes the loop element **130**, and an empty portion that includes everything except the loop element **130**. The length of a unit cell **120** in the X-direction can be referred to as the pitch in the X-direction, and is represented by the variable P_x . The length of a unit cell **120** in the Y-direction can be referred to as the pitch in the Y-direction, and is represented by the variable P_y .

The loop elements **130** are located such that the conductive plane **240**, the first and second vias **130A**, **130B**, and the first and second conductive surfaces **130C**, **130D** form a magnetic loop in and on the nonconductive layer **110** that couples strongly with the magnetic field in the regions between conductive plane **240** and IC die location represented by plane **260** (i.e. in the layer regions **110** and **250**). The largest length of a loop element **130** in the X-direction is represented by the variable L_x , while the gap between the loop element **130** and the edge of the unit cell **120** in the X-direction (i.e., the gap between adjacent loop elements **130**) is represented by the variable $L_{x'}$. The largest length of a loop element **130** in the Y-direction is represented by the variable L_y , while the gap between the loop element **130** and the edge of the unit cell **120** in the Y-direction (i.e., the gap between adjacent loop elements **130**) is represented by the variable $L_{y'}$. In the embodiment disclosed in FIGS. 1 to 3, the dimensions L_x and G_x are adjusted in conjunction with the adjustment in the gap dimension for a given height N_1 of the non-conductive layer **100**, i.e., a loop element **130** is produced in the non-conductive layer **110**.

The first and second vias **130A**, **130B** are openings located in the non-conductive layer **110** that are filled with a conductive material such as metal (e.g., copper, aluminum, or any other metal with a high electrical conductivity). The first via **130A** extends between the conductive plane **240** and the first conductive surface **130C**, while the second via **130B** extends between the conductive plane **240** and the second conductive surface **130D**.

The first and second conductive surfaces **130C**, **130D** are located on or over the non conductive layer **110** adjacent to each other. In the embodiment disclosed in FIGS. 1 to 3, the first and second conductive surfaces **130C**, **130D** each have a half-lozenge-shape, having a semicircular portion and a rectangular portion. The first and second conductive surfaces **130C**, **130D** are located with their rectangular ends adjacent so that together they form a lozenge-shape. If any gaps are restricted to the vias in non-conductive layer **110**, then the sections **130C** and **130D** will merge into a single lozenge-shape. In this case, sections **130C** and **130D** will abut against each other, leaving no gap between them.

4

In the embodiment described in FIGS. 1 to 3, the first and second vias **130A**, **130B** are cylindrical in shape, i.e. having a circular cross-section in the X-Y plane. (Although the cross-section of the cylinder is not restricted to having circular cross-section, and may have a differently shaped cross-section in other embodiments.) The first and second conductive surfaces **130C**, **130D** are located over the first and second vias **130A**, **130B** such that the circular cross-sections of the first and second vias **130A**, **130B** have the same center point in the X-Y plane as the semicircles in the first and second conductive surfaces **130C**, **130D**.

The first and second vias **130A**, **130B**, the first and second conductive surfaces **130C**, **130D**, and a portion of the conductive plane **240** form an almost continuous loop of conductive material, but for one or more gaps located either in or between the first and second vias **130A**, **130B** and the first and second conductive surfaces **130C**, **130D**. These gaps are shown in greater detail in FIGS. 2 to 6.

FIG. 2 is a cut-away view of the electromagnetic band gap device **100** of FIG. 1 along the line II-II', while FIG. 3 is a cut-away view of the electromagnetic band gap device of FIG. 1 along the line III-III'. In particular, FIG. 2 shows a cut-away view of the electromagnetic band gap device **100** in the X-Z plane, where the Z-direction is perpendicular to both the X-direction and the Y-direction, while FIG. 3 shows a cut-away view of the electromagnetic band gap device **100** in the Y-Z plane.

As shown in FIGS. 2 and 3, the non-conductive layer **110** is located over the conductive plane **240**, while the loop elements **130** are located in and on the non-conductive layer **110**. An integrated circuit (IC) die **260** is located above the non-conductive layer **110**, separated from the non-conductive layer **110** by a non-conductive gap **250**.

The conductive plane **240** is located of a conductive material such as a conductive metal (e.g., copper, aluminum, or any other electrically conductive material with a high electrical conductivity). This conductive plane **240** is used as a ground plane for an IC device formed on the IC die **260**.

The non-conductive gap **250** can be formed of any suitable filling that does not conduct electricity. For example, it could be a dielectric material, a gaseous material, a vacuum, or any other suitable material. As shown in FIG. 2, the non-conductive gap **250** comprises a solid dielectric. However, alternate embodiments can use a non-conductive gas as the non-conductive gap **250**. If the non-conductive gap **250** is a gaseous material or vacuum, supports will be located either on or adjacent to the array of unit cells **120** to support the IC die **260**.

In the disclosed embodiment, the IC die **260** contains an integrated circuit that uses the conductive plane **240** as a ground plane. In other embodiments, the IC die **260** may include a radio frequency (RF) element that transmits and/or receives radio waves, such as a radio transmitter or receiver, a radar transmitter or receiver, or the like.

In this disclosed embodiment, the first and second vias **130A**, **130B**, the first and second conductive surfaces **130C**, **130D**, and a portion of the conductive plane **240** form an almost continuous loop of conductive material, but for a first gap H_1 located between the first via **130A** and the conductive plane **240**. The first gap H_1 has a width of t . However, since the first gap H_1 is located adjacent to the conductive plane **240**, it has an effective gap length of $2t$, because of an image of the first gap H_1 that will be located in the conductive plane **240**.

Since the conductive plane **240** is used as ground plane for an IC device located on the IC die **260**, the first gap H_1 in each loop element **130** will cause the EM transmissions emanating from the conductive plane **240** to have a null frequency band,

i.e., a frequency band in which interfering signals from the conductive plane fall below a set threshold power. The precise location of the null frequency band is determined by the location of the first gap H_1 , the width t of the gap first H_1 , the dimensions of the unit cell **120** and the loop element **130** (i.e., P_X , L_X , G_X , P_Y , L_Y , and G_Y). These parameters can be altered as needed to get a null frequency band with a desired location and a desired frequency width. In some embodiments, G can vary from 100-200 μm , and P_Y can vary from 100-500 μm , with corresponding values for P_X , L_X , L_Y , and G_Y . However, these ranges are simply by way of example. Larger or smaller values of G_X and P_Y may be used.

In electronic terms, each loop element **130** operates as an LC resonant circuit, in conjunction with the conductive plane **240**. The resonant frequency of the loop element **130** will depend on the parameters of the loop element **130** (e.g., L_X , L_Y , the shape of the first and second conductive layers **130C**, **130D**, the number of gaps used, the position of the gaps, etc.)

Alternate Disclosed Embodiments

Numerous alternate embodiments will be described below. In each embodiment, similar numbers will represent the same elements. Where such elements are not named, they operate as described above with respect to comparable elements in the embodiment disclosed in FIGS. **1** to **3**.

Although a single gap H_1 is disclosed in the disclosed embodiment of FIGS. **1** to **3**, alternate embodiments could include multiple gaps. Furthermore, these gaps can be located anywhere within the loop element **130**. FIGS. **4** and **5** are side views of a unit cell **430**, **530** in an electromagnetic band gap device according to alternate disclosed embodiments. These alternate disclosed embodiments use different gap numbers and locations.

FIG. **4** is a side view of a unit cell in an electromagnetic band gap device **400**. As shown in FIG. **4**, five gaps are used in this electromagnetic band gap device **400**. A first gap H_1 is located between the conductive plane **240** and a first via **430A**; a second gap H_2 is located between the conductive plane **240** and a second via **430B**; a third gap H_3 is located between the first via **430A** and a first conductive layer **430C**; a fourth gap H_4 is located between the second via **430B** and a second conductive layer **430D**; and a fifth gap H_5 is located between the first conductive layer **430C** and the second conductive layer **430D**. Alternate embodiments could employ any one or more of these gaps H_1 , H_2 , H_3 , H_4 , H_5 .

FIG. **5** is a side view of a unit cell in an electromagnetic band gap device **500**. As shown in FIG. **5**, three gaps are used in this electromagnetic band gap device **500**. However, these gaps are located not at intersections between vias **530A**, **530B** and the conductive plane **240**; not between a via **530A**, **530B** and a corresponding conductive layer **530C**, **530D**; and not at an intersection of the conductive layers **530C**, **530D**. Rather, the gaps in this device **500** are located within a via **530A**, **530B**, or within a conductive layer **530C**. In particular, a sixth gap H_6 is located within the first via **530A**; a seventh gap H_7 is located within the second via **530B**; and an eighth gap H_8 is located in the first conductive layer **530C**. Alternate embodiments could use more or fewer gaps, and could place the gaps anywhere within the vias **530A**, **530B** or conductive layers **530C**, **530D**.

It is also possible in alternate embodiments to use a gap within a part of a loop element, and a gap at an intersection of parts of the loop element. For example, an embodiment might employ the first gap H_1 and the seventh gap H_7 . Any other combination of gap location and gap number is possible.

In addition, although the embodiments disclosed in FIGS. **1** to **5** are shown as having the non-conductive layer **110** having a height N_1 that is larger L_X or L_Y , alternate embodiments could vary the height of the non-conductive layer **110**. In particular, the height of the non-conductive layer **110** can be reduced below 100 μm for an EBG structure with a stop band near 80 GHz. FIG. **6** is a side view of a unit cell in an electromagnetic band gap device **600** according to still other disclosed embodiments.

As shown in FIG. **6**, a height N_2 of the non-conductive layer **610** is smaller than the value L_X . Furthermore, since this embodiment uses the same shape as FIGS. **1** to **3** for the first and second conductive layers **630C**, **630D**, L_X is greater than L_Y , meaning that N_2 is also smaller than L_Y . In this particular embodiment, N_2 is typically less than 200 μm for a Sienviper EBG structure.

Furthermore, although FIGS. **1** to **3** disclose the use of first and second conductive surfaces **130C**, **130D** that together form a lozenge shape, the precise shape of first and second conductive surfaces in a loop element can be varied in alternate embodiments. FIG. **7** is an overhead view of a loop element **730** in an electromagnetic band gap device **700** according to yet another disclosed embodiment. As shown in FIG. **7**, the first and second conductive surfaces **730C**, **730D**, which form the top of the loop element **730**, together form a barbell shape. However, this is merely by way of example, to demonstrate that alternate shapes can be used. First and second conductive surfaces in a loop element can be provided in numerous other shapes, so long as they can be properly connected to the vias in the loop element to interact properly with the magnetic field H in the conductive plane **240**.

Furthermore, although FIGS. **1** to **3** disclose the use of two conductive surfaces (first and second conductive surfaces **130C**, **130D**) that together form a lozenge shape, along with two vias (first and second vias **130A**, **130B**), alternate embodiments could employ more than two conductive surfaces and more than two vias. Embodiments with more vias will simply form additional loops with the conductive plane **240**.

FIG. **8** is an overhead view of a loop element **830** in an electromagnetic band gap device **800** according to still another disclosed embodiment. In particular, FIG. **8** illustrates a method to achieve attenuation in more than one direction within the plane of propagation. As shown in FIG. **8**, a loop element **830** includes four vias (**830A**, **830B**, **830C**, **830D**), and five conductive layers (**830E**, **830F**, **830G**, **830H**, **830I**). The four vias are arranged such that the first and second vias **830A**, **830B** form a first line, and third and fourth vias **830C**, **830D** form a second line perpendicular to the first line. The five conductive layers are configured such that they form a shape of two overlapping lozenges. However, this is merely by way of example, to demonstrate that alternate numbers of vias, with corresponding different numbers and shapes of conductive layers can be used. Alternate embodiments can use different numbers of vias, including odd numbers that are greater than 1.

Although not shown in FIG. **8**, gaps would be located in one or more of the vias **830A**, **830B**, **830C**, **830D** of the loop element **830**, as noted above with respect to the embodiments of FIGS. **1-7**.

In addition, although the embodiment disclosed in FIGS. **1** to **3** places the two vias **130A**, **130B** such that the center points of their circular cross-sections form a line in the X-direction (i.e., the direction of EM field propagation), alternate embodiments could form the unit cells **120** and the loop elements **130** such that they had some rotation in the X-Y plane (i.e., they were rotated around a center point such that

they were not entirely parallel with a line formed in the X-direction). In other words, the center points of the circular cross-sections of the two vias **130A**, **130B** could form a line that was some number of degrees rotated with respect to the X-direction.

Furthermore, although the embodiment disclosed in FIGS. **1** to **3** repeats the unit cells **120** and loop elements **130** using "perfect spacing" (i.e., P_x and P_y are constant for each unit cell), it is possible to add some small randomness to the spacing between loop elements **130**. Alternate embodiments could add some small randomness to the length of the unit cells **120** in the X-direction, the Y-direction, or both. This could be accomplished by making a length of a unit cell **120** in the X-direction equal to $P_x + \Delta$ —a random variance, and/or making a length of a unit cell **120** in the Y-direction equal to $P_y + \Delta$ —a random variance. Assuming L_x and L_y remain constant, this would have the effect of altering the one or both of G_x and G_y . In other words, a small randomness could be added to the gap between adjacent loop elements **130** in the X-direction, the Y-direction, or both. Adding such randomness would broaden the attenuation in frequency of the electromagnetic band gap device at the expense of sacrificing its maximum attenuation.

Frequency Nulls in an Antenna Using an Electromagnetic Band Gap Device

FIG. **9** is a graph of multiple sets of EBG attenuation responses **900** controlled by gap number, gap location, and unit cell parameters in an electromagnetic band gap device according to various disclosed embodiments. Each line in the graph of EBG suppression (i.e., attenuation) **900** represents a different set of parameters for gap number, gap location, and in it cell parameters. As shown in FIG. **9**, by manipulating these values, it is possible to create a wide variety of EBG suppression responses with a variety of different suppression and frequency response band gaps (i.e., widths of suppression in a frequency range).

Method of Making an Electromagnetic Band Gap Device

FIG. **10** is a flowchart of a method **1000** of manufacturing a loop element in an electromagnetic band gap device according to disclosed embodiments. As shown in FIG. **10**, the method **1000** begins by forming a conductive plane (**1005**). As noted above, this conductive plane can be made out of metal, or any other electrically conductive material. This can include metals, semi-metals, and semiconductors, though materials with lower electrical conductivities would provide a broader frequency band gap with lower suppression.

A non-conductive layer is formed over the conductive plane (**1010**). As noted above, this non-conductive layer can be made of a dielectric material, or any other solid material that does not conduct electricity.

Although operations **1005** and **1010** show first forming a conductive plane and then forming a non-conductive layer formed over the conductive plane, this could be reversed in alternate embodiments. In such embodiments a non-conductive layer could be formed first, and a conductive plane could then be formed over the non-conductive layer.

It is then determined whether there will be a gap in a first via (**1015**). If no gap is to be formed in the first via, the first via is formed in the nonconductive layer without a gap (**1020**). If, however, a gap is to be formed in the first via, the first via is formed in the non-conductive layer with a gap (**1025**).

It is then determined whether there will be a gap in a second via (**1030**). If no gap is to be formed in the second via, the second via is formed in the non-conductive layer without a gap (**1040**). If, however, a gap is to be formed in the second via, the second via is formed in the non-conductive layer with a gap (**1045**).

In each of these two operations, the vias can be formed and filled using any acceptable process. For example, in various embodiments the vias could be formed by drilling or etching. In various embodiments, these two processes can be performed sequentially or at the same time.

It is then determined whether there will be a gap in a first conductive layer (**1050**). If no gap is to be formed in the first conductive layer, the first conductive layer is formed over the first via without a gap (**1060**). If, however, a gap is to be formed in the first conductive layer, the first conductive layer is formed over the first via with a gap (**1065**).

Finally, it is determined whether there will be a gap in a second conductive layer (**1070**). If no gap is to be formed in the second conductive layer, the second conductive layer is formed over the second via without a gap (**1080**). If, however, a gap is to be formed in the second conductive layer, the second conductive layer is formed over the second via with a gap (**1085**).

In each of these two operations, the conductive layers can be formed using any acceptable process. For example, in various embodiments the vias could be formed by physical vapor deposition (PVD), chemical vapor deposition (CVD), electrochemical deposition (ECD), molecular beam epitaxy (MBE), atomic layer deposition (ALE)), or the like. In various embodiments, these two processes can be performed sequentially or at the same time.

The first and second vias and the first and second conductive layers are formed out of a conductive material, such as copper, aluminum, or conductive epoxy (e.g., an epoxy loaded with silver particles).

Passing through this method once will create a single loop element over a conductive plane. However, operations **1015** through **1085** can then be repeated, as necessary, to create an array of loop elements over the conductive plane. In such a case, it is necessary to move to a new location each time operations **1015** through **1085** are carried out. In various embodiments, the multiple iterations of this method can be performed sequentially or at the same time.

In the above method, a gap in a via can refer to: a gap at an internal portion of a via; a gap at an intersection of a via and the conductive plane; or a gap at an intersection of a via and a conductive layer. Similarly, a gap in a conductive layer can refer to: a gap at an internal portion of a conductive plane; a gap at an intersection of a via and a conductive layer; or a gap between the conductive layers. Furthermore, although operations **1015**, **1030**, **1050**, and **1070** to determine whether a gap is required in a given element, and operations **1025**, **1045**, **1065**, and **1085** all indicate forming an element with a gap, these operations can easily be applied to situations in which multiple gaps are to be formed in a given element.

A device is provided, comprising: a conductive plane configured to propagate electro-magnetic fields in a first direction, and to have a magnetic field in a second direction perpendicular to the first direction; a non-conductive substrate located over the conductive plane; and an electromagnetic band gap unit cell, the electromagnetic band gap unit cell including a first via located in the non-conductive substrate, the first via being filled with a conductive material, a second via located in the non-conductive substrate, the second via being filled with the conductive material, a first conductive surface located on the non-conductive substrate over the first via, and a second conductive surface located on the non-conductive substrate over the second via, wherein the first and second vias are arranged to form a line in the first direction, the electromagnetic band gap unit cell is configured to operate as an LC resonant circuit in conjunction with the conductive plane, wherein at least one gap is located in the electromag-

netic band gap unit cell, the at least one gap being located: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

The non-conductive layer may comprise a non-conductive dielectric material. The non-conductive gap may comprise one of: air, vacuum, or a non-conductive dielectric material.

The at least one electromagnetic band gap unit cell may comprise a plurality of electromagnetic band gap unit cells arranged in the first direction to form an electromagnetic band gap cell row. The at least one electromagnetic band gap unit cell may comprise a plurality of electromagnetic band gap unit cells arranged in an array having rows extending in the first direction and columns extending in the second direction to form an electromagnetic band gap cell array.

The device may further comprise: a top layer located over the non-conductive layer, wherein a non-conductive gap is located between the non-conductive layer and the top layer.

The device, wherein each individual electromagnetic band gap unit cell in the electromagnetic band gap unit cell row has an orientation that differs from a reference line by a random angular difference around a center point of the individual electromagnetic band gap unit cell.

A plurality of gaps may be located in the electromagnetic band gap unit cell, the plurality of gaps being located in at least two of: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

The non-conductive substrate may have a thickness under 200 μm .

An array is provided, comprising: a conductive plane configured to propagate electro-magnetic fields in a first direction, and to have a magnetic field in a second direction perpendicular to the first direction; a non-conductive substrate located over the conductive plane; and a plurality of electromagnetic band gap cells located in a regular array in the non-conductive substrate, wherein each electromagnetic band gap unit cell includes a first via located in the non-conductive substrate, the first via being filled with a conductive material, a second via located in the non-conductive substrate, the second via being filled with the conductive material, a first conductive surface located on the non-conductive substrate over the first via, and a second conductive surface located on the non-conductive substrate over the second via, the first and second vias are arranged to form a line in the first direction, the electromagnetic band gap unit cell is configured to operate as an LC resonant circuit in conjunction with the conductive plane, at least one gap is located in the electromagnetic band gap unit cell, and the at least one gap being located: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

A first group of electromagnetic band gap unit cells from among the plurality of electromagnetic band gap unit cells may have at least one gap located according to a first configuration,

and a second group of electromagnetic band gap unit cells from among the plurality of electromagnetic band gap unit cells may have at least one gap located according to a second configuration that is different from the first configuration.

The non-conductive gap may comprise one of: air, vacuum, or a non-conductive dielectric material. The non-conductive substrate may have a thickness under 200 μm .

The array may further comprise: a top layer located over the non-conductive layer, wherein a non-conductive gap is located between the non-conductive layer and the top layer.

In each electromagnetic band gap cell, a plurality of gaps may be located in the electromagnetic band gap unit cell, the plurality of gaps being located in at least two of: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

A method of making an electromagnetic band gap device is provided, comprising: forming a conductive plane; forming a non-conductive substrate over the conductive plane; forming a first via in the non-conductive substrate, the first via being filled with a conductive material; forming a second via in the non-conductive substrate, the second via being filled with the conductive material; forming a first conductive surface on the non-conductive substrate over the first via; forming a second conductive surface on the non-conductive substrate over the second via; and forming at least one gap either between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane, wherein the first and second vias are arranged to form a line in the first direction, the first via, the second via, the first conductive surface, and the second conductive surface form an electromagnetic band gap unit cell, and the electromagnetic band gap unit cell is configured to operate as an LC resonant circuit in conjunction with the conductive plane.

The non-conductive gap may comprise one of: air, vacuum, or a non-conductive dielectric material.

The operations of forming the first via, forming the second via, forming the first conductive surface, and forming the second conductive surface on the nonconductive substrate over the second via may be repeated a plurality of times to form a row of electromagnetic band gap cells. In the operation of forming the second via, the second via may be formed such that a line between the center of the first via and the center of the second via is rotated a random angular amount with respect to a reference line. The operations of forming a first via, forming a second via, forming a first conductive surface, and forming a second conductive surface on the nonconductive substrate over the second via may be repeated a plurality of times to form an array of electromagnetic band gap cells.

When the operations of forming a first via, forming a second via, forming a first conductive surface, and forming a second conductive surface on the nonconductive substrate over the second via are repeated a plurality of times, the repetitions may be conducted at the same time as each other.

The method may further comprise forming a plurality of gaps in at least two of: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between

11

the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

The nonconductive substrate may be formed to have a thickness under 200 μm .

CONCLUSION

This disclosure is intended to explain how to fashion and use various embodiments in accordance with the invention rather than to limit the true, intended, and fair scope and spirit thereof. The foregoing description is not intended to be exhaustive or to limit the invention to the precise form disclosed. Modifications or variations are possible in light of the above teachings. The embodiment(s) was chosen and described to provide the best illustration of the principles of the invention and its practical application, and to enable one of ordinary skill in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. All such modifications and variations are within the scope of the invention as determined by the appended claims, as may be amended during the pendency of this application for patent, and all equivalents thereof, when interpreted in accordance with the breadth to which they are fairly, legally, and equitably entitled. The various circuits described above can be implemented in discrete circuits or integrated circuits, as desired by implementation.

What is claimed is:

1. A device, comprising:

a conductive plane configured to propagate electromagnetic fields in a first direction, and to have a magnetic field in a second direction perpendicular to the first direction;

a non-conductive substrate located over the conductive plane; and

at least one electromagnetic band gap unit cell, the at least one electromagnetic band gap unit cell including

a first via located in the non-conductive substrate, the first via being filled with a conductive material,

a second via located in the non-conductive substrate, the second via being filled with the conductive material,

a first conductive surface located on the non-conductive substrate over the first via, and

a second conductive surface located on the non-conductive substrate over the second via,

wherein

the first and second vias are arranged to form a line in the first direction,

the at least one electromagnetic band gap unit cell is configured to operate as an LC resonant circuit in conjunction with the conductive plane,

wherein at least one gap is located in the at least one electromagnetic band gap unit cell, the at least one gap being located: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

2. The device of claim 1, wherein the non-conductive layer comprises a non-conductive dielectric material.

3. The device of claim 1, wherein the gap is a non-conductive gap that comprises one of:

air, vacuum, or a non-conductive dielectric material.

12

4. The device of claim 1, wherein the at least one electromagnetic band gap unit cell comprises a plurality of electromagnetic band gap unit cells arranged in the first direction to form an electromagnetic band gap cell row.

5. The device of claim 1, wherein the at least one electromagnetic band gap unit cell comprises a plurality of electromagnetic band gap unit cells arranged in an array having rows extending in the first direction and columns extending in the second direction to form an electromagnetic band gap cell array.

6. The device of claim 4, further comprising:

a top layer located over the non-conductive layer, wherein

a non-conductive gap is located between the non-conductive layer and the top layer.

7. The device of claim 4, wherein each individual electromagnetic band gap unit cell in the electromagnetic band gap unit cell row has an orientation that differs from a reference line by a random angular difference around a center point of the individual electromagnetic band gap unit cell.

8. The device of claim 1, wherein the at least one gap is located: between the first via and the first conductive surface, between the first conductive surface and the second conductive surface, or between the second conductive surface and the second via, in the second via.

9. The device of claim 1, further wherein a plurality of gaps are located in the electromagnetic band gap unit cell, the plurality of gaps being located in at least two of: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

10. The device of claim 1, wherein the non-conductive substrate has a thickness under 200 μm .

11. An array, comprising:

a conductive plane configured to propagate electromagnetic fields in a first direction, and to have a magnetic field in a second direction perpendicular to the first direction;

a non-conductive substrate located over the conductive plane; and

a plurality of electromagnetic band gap cells located in a regular array in the non-conductive substrate, wherein

each electromagnetic band gap unit cell includes

a first via located in the non-conductive substrate, the first via being filled with a conductive material,

a second via located in the non-conductive substrate, the second via being filled with the conductive material,

a first conductive surface located on the non-conductive substrate over the first via, and

a second conductive surface located on the non-conductive substrate over the second via,

the first and second vias are arranged to form a line in the first direction,

each electromagnetic band gap unit cell is configured to operate as an LC resonant circuit in conjunction with the conductive plane, and

at least one gap is located in each electromagnetic band gap unit cell, the at least one gap being located in at least one of the group consisting of: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, in the second conductive surface, between the sec-

13

ond conductive surface and the second via, in the second via, or between the second via and the conductive plane.

12. The array of claim 11, wherein

a first group of electromagnetic band gap unit cells from among the plurality of electromagnetic band gap unit cells have at least one gap located according to a first configuration, and

a second group of electromagnetic band gap unit cells from among the plurality of electromagnetic band gap unit cells have at least one gap located according to a second configuration that is different from the first configuration.

13. The array of claim 11, wherein the gap is a non-conductive gap that comprises one of:

air, vacuum, or a non-conductive dielectric material.

14. The array of claim 11, wherein the non-conductive substrate has a thickness under 200 μm .

15. The array of claim 14, further comprising:

a top layer located over the non-conductive layer, wherein

a non-conductive gap is located between the non-conductive layer and the top layer.

16. The array of claim 11, further wherein in each electromagnetic band gap cell, a plurality of gaps are located in the electromagnetic band gap unit cell, the plurality of gaps being located in at least two of the group consisting of: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

17. A method of making a device, comprising:

forming a conductive plane;

forming a non-conductive substrate;

forming a first via in the non-conductive substrate, the first via being filled with a conductive material;

forming a second via in the non-conductive substrate, the second via being filled with the conductive material;

forming a first conductive surface on the non-conductive substrate over the first via;

forming a second conductive surface on the non-conductive substrate over the second via; and

forming at least one gap either between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane,

14

wherein

the non-conductive substrate is located adjacent to the conductive plane,

the first and second vias are arranged to form a line in a first direction,

the first via, the second via, the first conductive surface, and the second conductive surface form an electromagnetic band gap unit cell, and

the electromagnetic band gap unit cell is configured to operate as an LC resonant circuit in conjunction with the conductive plane.

18. The method of claim 17, wherein the gap is a non-conductive gap that comprises one of the group consisting of: air, vacuum, or a non-conductive dielectric material.

19. The method of claim 17, wherein the operations of forming the first via, forming the second via, forming the first conductive surface, and forming the second conductive surface on the non-conductive substrate over the second via are repeated a plurality of times to form a row of electromagnetic band gap cells.

20. The method of claim 19, when the operations of forming the first via, forming the second via, forming the first conductive surface, and forming the second conductive surface on the non-conductive substrate over the second via are repeated a plurality of times, the repetitions are conducted at the same time as each other.

21. The method of claim 19, wherein in the operation of forming the second via, the second via is formed such that a line between the center of the first via and the center of the second via is rotated a random angular amount with respect to a reference line.

22. The method of claim 17, wherein the operations of forming a first via, forming a second via, forming a first conductive surface, and forming a second conductive surface on the non-conductive substrate over the second via are repeated a plurality of times to form an array of electromagnetic band gap cells.

23. The method of claim 22, when the operations of forming a first via, forming a second via, forming a first conductive surface, and forming a second conductive surface on the non-conductive substrate over the second via are repeated a plurality of times, the repetitions are conducted at the same time as each other.

24. The method of claim 17, further comprising forming a plurality of gaps in at least two of: between the conductive plane and the first via, in the first via, between the first via and the first conductive surface, in the first conductive surface, between the first conductive surface and the second conductive surface, in the second conductive surface, between the second conductive surface and the second via, in the second via, or between the second via and the conductive plane.

25. The method of claim 17, wherein the non-conductive substrate is formed to have a thickness under 200 μm .

* * * * *